# Part I:

Beamline Simulation for the VLADD Experiment

Georgia Karagiorgi

## Overview

#### **VLAnd extra Dimensions Detector:**

Search for Positronium "invisible" decays at BR <  $10^{-7}$  (ideally, BR =  $10^{-10}$ ; limit from previous experiments: BR >  $10^{-6}$ )

## We're looking for:

```
pPs \rightarrow < 2\gamma,
or, oPs \rightarrow < 3\gamma
```

**Positronium 101:** 

 $pPs \rightarrow 2\gamma$  (τ = 0.125ns) orthopositronium (oPs): Triplet state |1,1>, |1,0>, |1,-1>  $oPs \rightarrow 3\gamma$  (τ = 0.142μs)

...missing energy in Ps decay products

## **Motivation**

#### Theoretical motivation:

Ps is a great system for the study of new Physics in low E scale!

**Mirror Matter/Dark Matter** 

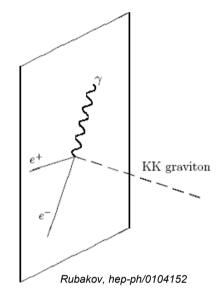
**Extra-D** 

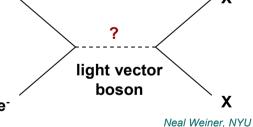
**Invisible Z decay** 

Milli-charged particles

New, light, vector bosons

. . .





e<sup>+</sup>

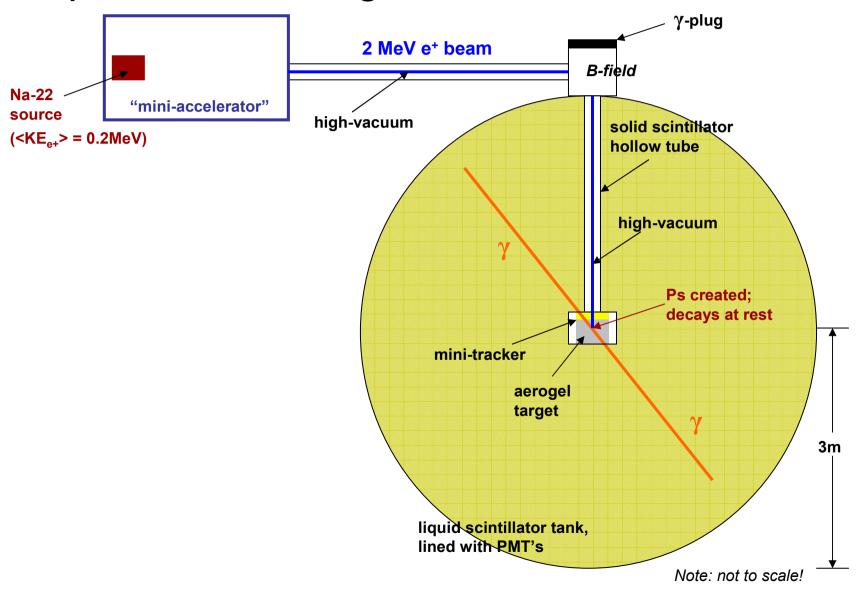
#### **Experimental motivation:**

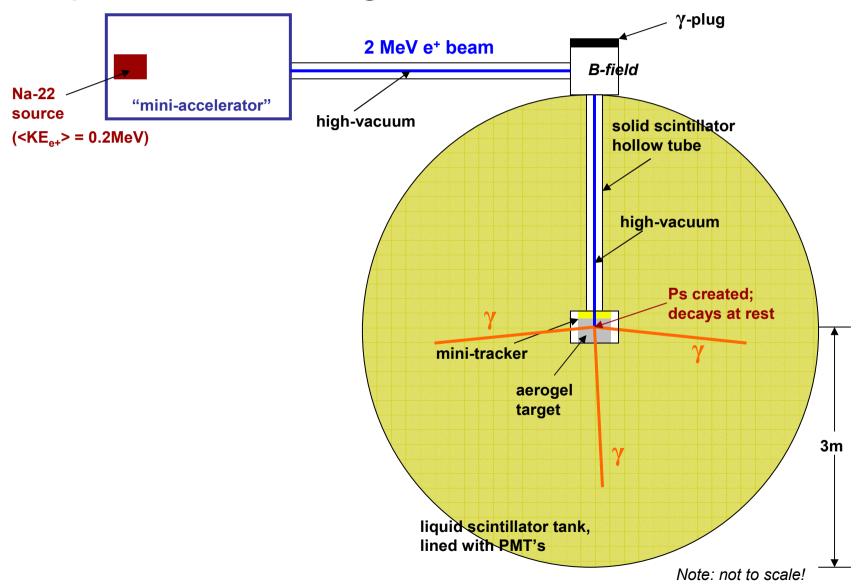
\*Prototype\* for preliminary testing available

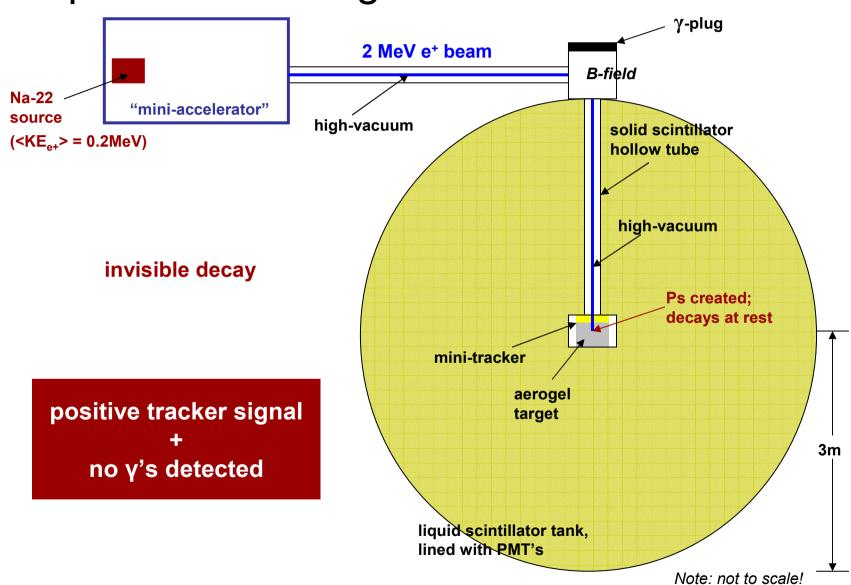
Current limits on oPs invisible decay >10<sup>-6</sup> (Mitsui et. al., 1992)

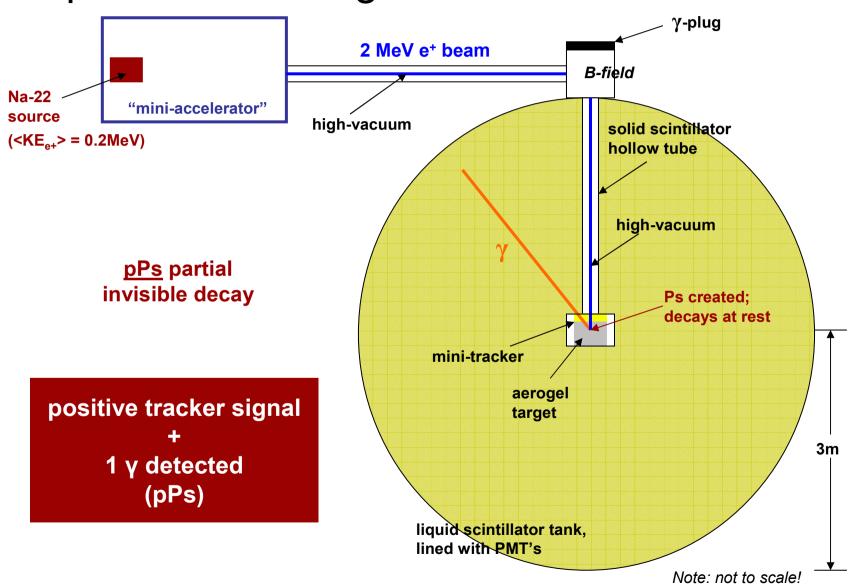
(ETH proposed limit: 10<sup>-8</sup>)

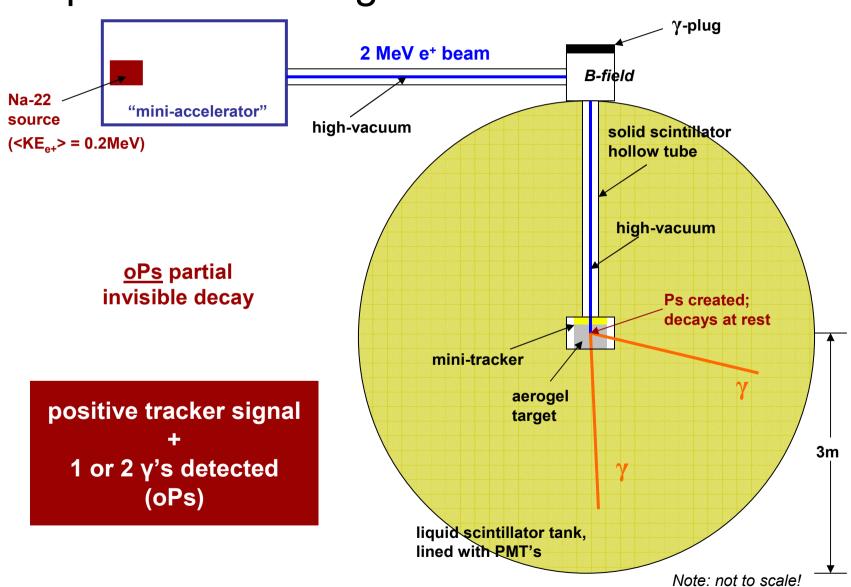
Ann Nelson, UW











# Challenges

positron in  $\rightarrow$  "nothing" out (BR < 10<sup>-7</sup>) or, positron in  $\rightarrow$  "not everything" out

"Nothing" is important! We really need to be able to tell "nothing" from "something" (i.e.  $\gamma$ 's). Therefore, we need to be able to detect  $\gamma$ 's with inefficiency <  $10^{-7}$ !

#### We need an (almost) entirely active detector to achieve such high sensitivity

- Making the beam pipe and tracker/target enclosure out of scintillator
- •Keeping blind regions (vacuum, target) as small as possible
- •Achieving high  $\gamma$ -detection efficiency (materials, etc)

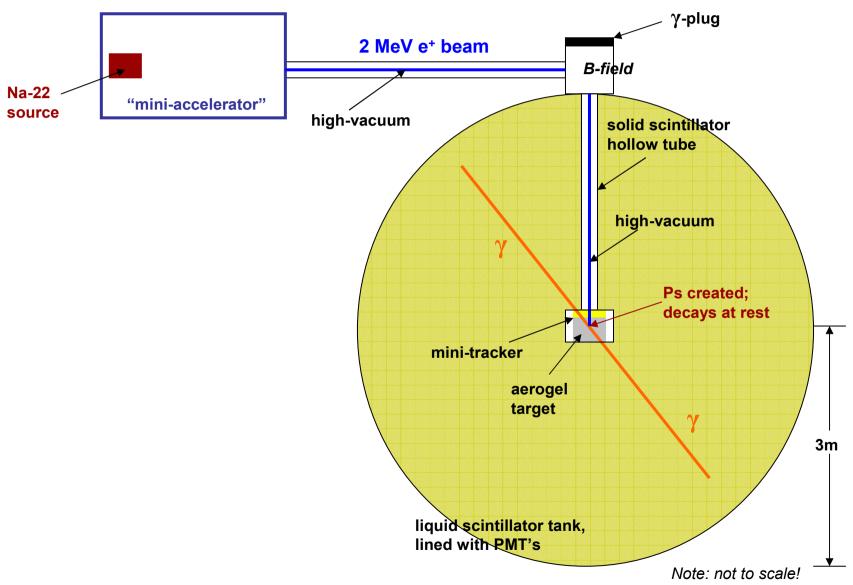
#### We need very good event reconstruction

- •Keeping the **target** region as **small** as possible
- Using fast scintillators
- •Looking into **G4 physics** reliability at such low energy, BR regimes

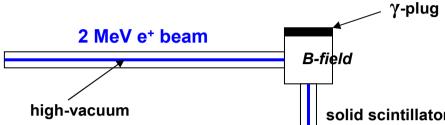
#### We need extremely low background

- •Going underground (Soudan, Homestake,...)
- Using coincidence/timing trigger
- Using strong discrimination techniques

# My tiny contribution...

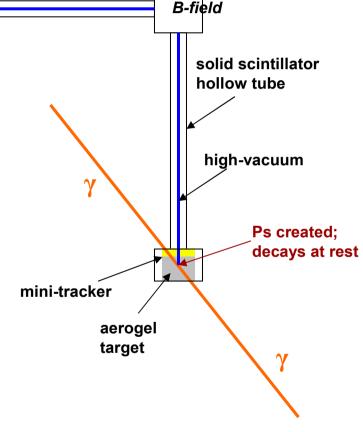


# My tiny contribution...

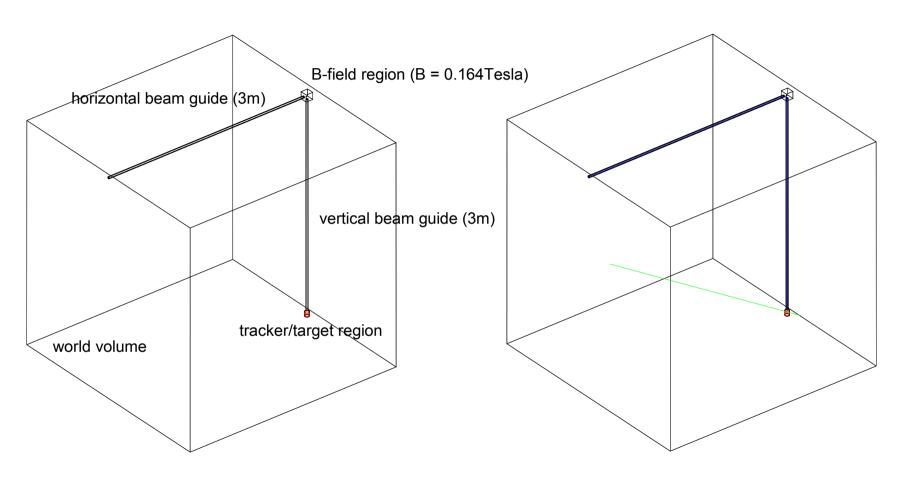


#### Questions to answer...

- Min beam energy / tracker thickness for "good" track
- Possible e<sup>+</sup> trajectories as it leaves the tracker
- Max variation of beam energy allowed by B-field and geometry
- Target material (aerogel, MgO, SiO)
- Min target size to stop positron
- Tube / target container thickness and material
- Efficiency of γ absorption in various regions
- Obstruction of e<sup>+</sup> track by debris
- Outgassing effects



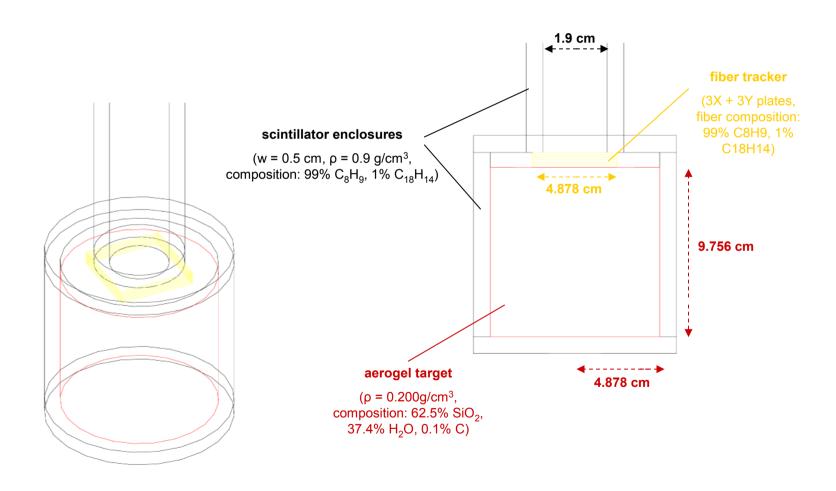
Note: not to scale!



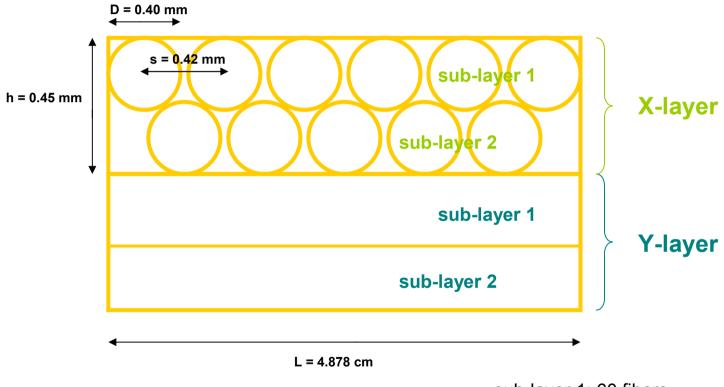
empty scene

one positron event

Zoom in on Tracker and Target region: Empty scene



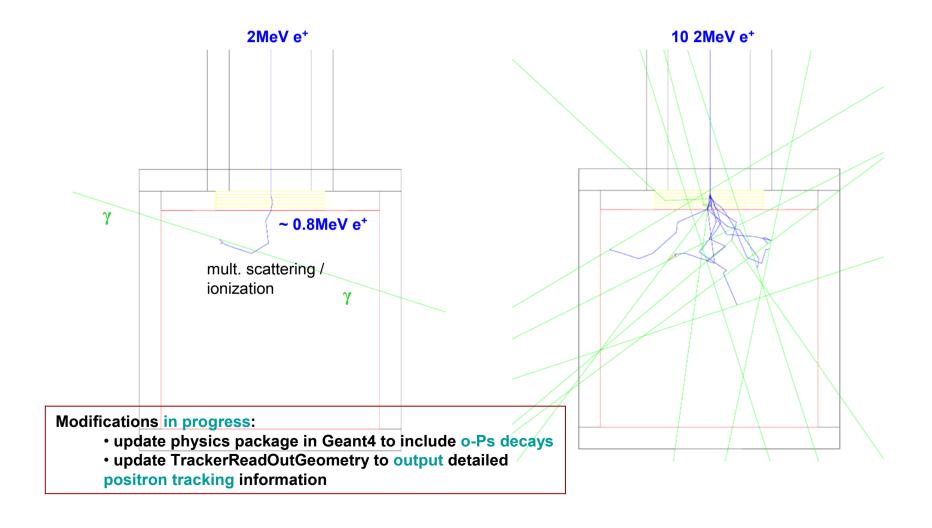
## Fiber tracker layers



sub-layer 1: 60 fibers sub-layer 2: 59 fibers

e⁺ energy after exiting tracker ≤ 1 MeV

Zoom in on Tracker and Target region: 1 and 10 events



## Simulation results

Min beam energy / tracker thickness for "good" track:

E = 2MeV / 6 tracker layers (3X+3Y), (60+59) fibers per layer, D = 0.40mm

- Possible e<sup>+</sup> trajectories as it leaves the tracker: *In progress* ...
- Max variation of beam energy allowed:

for B = 0.164Tesla (for specific geometry/positron E)  $\rightarrow \Delta E \sim \pm 0.3\%$ 

- Target material: aerogel (still considering other options)
- Min target size to stop positron: for aerogel, < 10x10x10 cm<sup>3</sup>
- Tube / target+tracker container thickness and material: 0.5cm, scintillator
- Obstruction of e<sup>+</sup> track by debris: In progress ...
- Outgassing effects:

vacuum pressure =  $10^{-8}$  Torr (ideal); *R&D studies for outgassing in progress* 

• Efficiency of γ absorption in various regions: In progress ...

## Preliminary R&D studies

Decide on ideal combination of materials to avoid issues such as:

- Solid scintillator outgassing (under high vacuum)
- Solid scintillator degradation in pseudocumin (scintillator oil dopant)

Currently in contact with BICRON and Kyraray
Out-gassing studies planned with Eileen Hahn, FNAL
Degradation tests planned with Anna Pla-Dalmau, FNAL

## Conclusion

- Framework available for optimization of important beamline parameters:
  - Positron energy (2MeV ± 0.3%)
  - Beam tube material/dimensions (3m long, 1.9cm ID)
  - B-field (0.164Tesla for specific geometry/positron E)
  - Vacuum pressure (ideal, 10<sup>-8</sup> Torr)
  - Tracker material/thickness (scintillator, 2.70mm total thickness)
  - Target material/size (aerogel, 9.8x9.8cm²)
- Beamline simulation \*ready\* to be combined with detector tank simulation (Bill Seligman, Nevis Labs), and accelerator simulation (Muons, Inc.)

#### Work in progress:

- include o-Ps decays
- output positron tracking
- verify Geant4 reliability in low E regime
- test scintillator outgassing/degradation

## Special thanks to...

Janet Conrad, for valuable input and advice
Bill Seligman, for help with Geant4
Dave Schmitz and Mike Wilkins, for help with Geant4

# Part II:

Leptonic CP Violation Studies at MiniBooNE in a (3+2) Sterile v Hypothesis

Georgia Karagiorgi

## **Motivation**

## 3 experimental signatures for neutrino oscillations:

solar  $v_e$  oscillations

 $\begin{array}{c} \text{atmospheric} \\ v_{\mu} \text{ oscillations} \end{array}$ 

 $\begin{array}{c} \textbf{LSND} \\ \overline{v}_{\mu} \rightarrow \overline{v}_{e} \end{array}$ 

$$\Delta m_{solar}^2 + \Delta m_{atm}^2 \neq \Delta m_{LSND}^2$$



#### 3 independent mass splittings !?!

- 1. Introduce different mass spectra for v and  $\overline{v}$  sector
  - → CPT violation
- 2. Add extra neutrinos with non-standard weak couplings
  - → sterile neutrinos ★

# (3+2) Sterile v models

Add 2 extra neutrinos with *non-standard weak couplings* (sterile v's)

2 sterile v's 
$$(m_4, m_5)$$

$$\begin{array}{c}
5 \\
4 \\
\hline
\end{array}$$

$$\Delta m^2_{LSND} \sim 1 - 10 \text{ eV}^2$$
3 active v's  $(m_1, m_2, m_3)$ 

$$\begin{array}{c}
3 \\
2 \\
\hline
\end{array}$$

$$\Delta m^2_{atm} \sim 10^{-3} \text{ eV}^2$$

$$\Delta m^2_{solar} \sim 10^{-4} \text{ eV}^2$$

Sorel et. al., hep-ph/0305255

## Sterile neutrino formalism and CP violation

#### General v oscillation formula:

$$P(\nu_{\alpha} \to \nu_{\beta}) = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathcal{R}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 x_{ij} + 2 \sum_{i>j} \mathcal{I}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin 2x_{ij}$$

 $\alpha, \beta \equiv e, \mu, \tau$ , or sterile flavor

$$i, j = 1, \ldots, N$$

$$x_{ij} \equiv 1.27 \Delta m_{ij}^2 L/E$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

#### For (3+2) models:

approximate  $m_1 = m_2 = m_3 = 0$ \*

two independent mass splittings:  $\Delta m^2_{41}$ ,  $\Delta m^2_{51}$ 

four moduli:  $|U_{e4}|$ ,  $|U_{\mu4}|$ ,  $|U_{e5}|$ ,  $|U_{\mu5}|$ 

one CPV phase:  $\varphi_{54} = arg(U^*_{\mu 5} U_{e5} U_{\mu 4} U^*_{e4})$ 

Note: For  $\overline{v}$  oscillations,  $\varphi_{54} \rightarrow -\varphi_{54}$ 

```
* This allows for 6 → 1 CPV phase in a (3+2) hypothesis (3 → 0 CPV phases in a (3+1) hypothesis) (1 → 0 CPV phases in a (3+0) hypothesis)
```

(3+2) model = most minimalistic model for CPV studies

Combine and analyze oscillation results from the short base-line (SBL) experiments in a 3 active + 2 sterile v hypothesis, and generate models with varying parameters:

 $\Delta m_{4l}^2$ ,  $\Delta m_{5l}^2$ ,  $|U_{e4}|$ ,  $|U_{\mu 4}|$ ,  $|U_{e5}|$ ,  $|U_{\mu 5}|$ , and  $\varphi_{54}$ , that fit the SBL oscillation data best.

For best models ( $\chi^2 < 152.0$ , d.o.f. = 145),

Probe the <u>oscillation probabilities</u> in neutrino (p) and anti-neutrino ( $\bar{p}$ ) modes at MiniBooNE, and <u>oscillation significances</u> ( $p/\delta p$  and  $\bar{p}/\delta \bar{p}$ ) in:

- 1. CP-Conserving case (CPC)
- 2. CP-Violating case (CPV)

Analyze the <u>CPV phase space</u> allowed for best fit models, and the <u>CP asymmetry significance</u>  $(A_{CP}/\delta A_{CP})$  as a function of CPV-phase  $\phi_{54}$ 



**CDHS** 

CCFR84

**KARMEN** 

**NOMAD** 

**LSND** 

+

Atmospheric constaint

Combine and analyze oscillation results from the short base-line (SBL) experiments in a 3 active + 2 sterile v hypothesis, and generate models with varying parameters:  $\Delta m^2_{4I}$ ,  $\Delta m^2_{5I}$ ,  $|U_{e4}|$ ,  $|U_{\mu4}|$ ,  $|U_{e5}|$ ,  $|U_{\mu5}|$ , and  $\varphi_{5\Phi}$  that fit the SBL oscillation data best.

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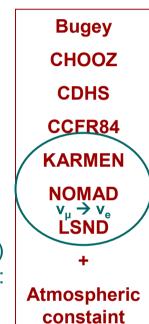
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Bugey
CHOOZ
CDHS
CCFR84
KARMEN
NOMAD
LSND
+
Atmospheric
constaint
+ \chi^2, + 1dof
er limit on high An

(Super-K, K2K)

# MC analysis method

- $0.1eV^2 \le \Delta m_{4l}^2$ ,  $\Delta m_{5l}^2 \le 100eV^2$ , where  $\Delta m_{5l}^2 \ge \Delta m_{4l}^2$
- $|U_{e4}|$ ,  $|U_{\mu4}|$ ,  $|U_{e5}|$ ,  $|U_{\mu5}|$ , are randomly generated, satisfying:  $U_{ei}^{\ \ 2} + U_{\mu i}^{\ \ 2} \leq 0.5$ , and  $U_{\alpha 4}^{\ \ 2} + U_{\alpha 5}^{\ \ 2} \leq 0.5$
- Neutrino masses and mixings are generated by importance sampling via a Markov chain MC

Model acceptance probability: 
$$P(x_i \rightarrow x_{i+1}) = min\{1, \exp[-(\chi_{i+1}^2 - \chi_i^2)/T]\}$$
 
$$x_{i+1} = x_i + e$$

Allowed regions are determined using Gaussian approx. method

# Main goal

- Verify previous analysis done by Michel Sorel (Sorel et. al., hep-ph/0305255)
- Update the existing code to take into account atmospheric constraint and reproduce models (Maltoni et. al., hep-ph/0405172)



Reproduce models with updated MiniBooNE sensitivities
 (using new updated v cross-sections, MiniBooNE flux, v<sub>e</sub> cuts, detector response signal, systematic uncertainties)

(In progress)

# Results: MiniBooNE oscillation probabilities

oscillation probability in neutrino (p) and anti-neutrino (p) mode (MiniBooNE):

$$\stackrel{(-)}{p}_{BooNE} = \frac{\int dE \ p(\nu_{\mu} \to \nu_{e}) [\stackrel{(-)}{N}_{0} \ (\nu) + \stackrel{(-)}{N}_{0} \ (\bar{\nu})]}{\int dE \ [\stackrel{(-)}{N}_{0} \ (\nu) + \stackrel{(-)}{N}_{0} \ (\bar{\nu})]}$$

 $(\overline{N}_{\theta}(v), \overline{N}_{\theta}(\overline{v}))$  = neutrino, anti-neutrino **full transmutation rate distributions** as a function of neutrino (anti-neutrino) energy in neutrino (anti-neutrino) mode

calculated using v cross-sections, MiniBooNE v flux,  $v_{\rm e}$  cuts, and detector signal response

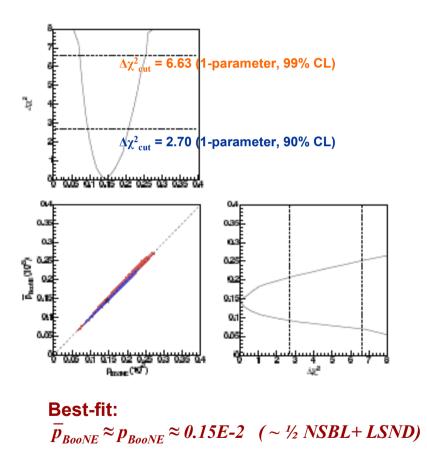
E = neutrino energy

CPC:  $\varphi_{54} = \theta$ , or  $\pi$ CPV:  $\theta \le \varphi_{54} \le 2\pi$ 

$$P(\nu_{\alpha} \to \nu_{\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathcal{R}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 x_{ij} + 2\sum_{i>j} \mathcal{I}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin 2x_{ij}$$

## Results: MiniBooNE oscillation probabilities

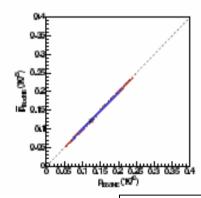
## CP-conserving (3+2) models



without atm constraint

# Best-fit (atm): $\overline{p}_{BooNE} \approx p_{BooNE} \approx 0.13E-2$

Similar allowed  $p_{BooNE}$ ,  $\overline{p}_{BooNE}$  ranges for the same  $\Delta \chi^2$  cuts

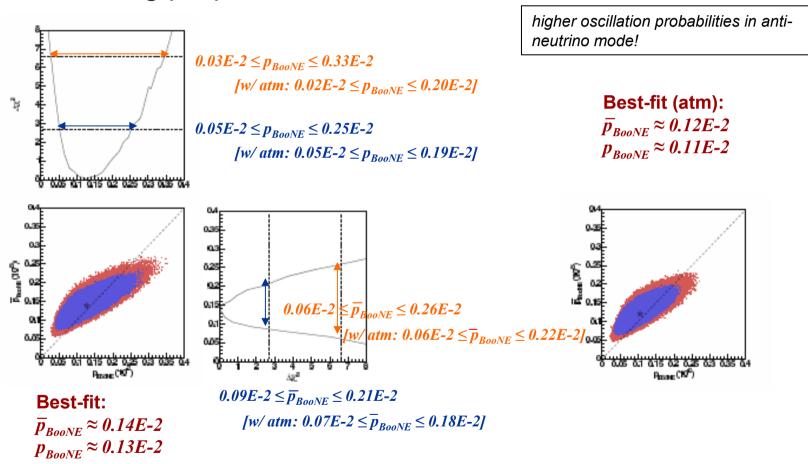


99% CL ( $\Delta \chi^2$  < 9.21, 2-param) 90% CL ( $\Delta \chi^2$  < 4.61, 2-param)

with atm constraint

## Results: MiniBooNE oscillation probabilities

#### CP-violating (3+2) models



without atm constraint

with atm constraint

**oscillation significance** in neutrino (p) and anti-neutrino ( $\bar{p}$ ) mode calculated for a counting experiment for 1.0x10<sup>21</sup> p.o.t., for both v and  $\bar{v}$ :

$$p_{BooNE}/\delta p_{BooNE}$$
,  $\bar{p}_{BooNE}/\delta \bar{p}_{BooNE}$ 

 $\delta p_{BooNE}$ ,  $\delta \bar{p}_{BooNE} = 1\sigma$  uncertainties in  $p_{BooNE}$ ,  $\bar{p}_{BooNE}$ 

include both statistical uncertainties in oscillation signal prediction, and systematic uncertainty of background prediction

| Background Source            | Uncertainty |
|------------------------------|-------------|
| Intrinsic v <sub>e</sub> :   |             |
| from K+ decay                | 0.05        |
| from K <sup>0</sup> decay    | 0.06        |
| from µ decay                 | 0.05        |
| ν <sub>μ</sub> miss-ID:      |             |
| NC/Coherent π <sup>0</sup>   | 0.05        |
| $\Delta \rightarrow N\gamma$ | 0.20        |
| Reconstruction:              |             |
| Energy Scale                 | 0.05        |
| Efficiency and Selection     | 0.05        |

Table 1: Systematic error assumptions considered

Table 2: Best Fit Model Parameters and Statistics, CPC

| Δm <sup>2</sup> <sub>41</sub><br>(eV <sup>2</sup> ) | $\Delta m^2_{51}$ (eV <sup>2</sup> ) | $ U_{e4} $ | $ U_{\mu 4} $ | $ U_{e5} $ | $ U_{\mu 5} $ | p<br>(%) | <del>p</del><br>(%) | $\varphi_{54}$ | $\chi^2$ | d.o.f. | Signal input after cuts (10 <sup>21</sup> p.o.t.) | Background<br>levels  | <i>p/δp</i> (σ) | $\overline{p}/\delta p^{-}$ $(\sigma)$ |
|---|--------------------------------------|------------|---------------|------------|---------------|----------|---------------------|----------------|----------|--------|---|---|-----------------|--|
| 0.92  | 21                                   | 0.128      | 0.184         | 0.441      | 0.217         | 0.146    | 0.144               | 0              | 135.19   | 145    | ~300  | $\begin{array}{cccc} v_{\mu}  \textit{Mis-ID} & 353 \\ \Delta \rightarrow N \gamma & 1077 \\ v_{\varepsilon}  (\textit{K}^{+}) & 116 \\ v_{\varepsilon}  (\textit{K}^{\theta}) & 38 \\ v_{\varepsilon}  (\textit{K}^{\theta}) & 192 \\ \end{array}$ | 5.36            | 3.94                                   |
| 0.92  | 24                                   | 0.132      | 0.158         | 0.066      | 0.159         | 0.125    | 0.123               | 0              | 141.4    | 146    |   |   | 4.36            | 3.27                                   |

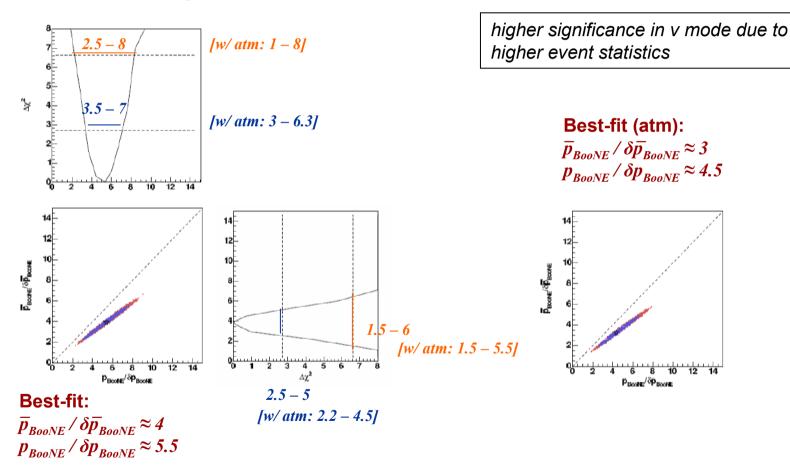
with atmospheric constraint

Table 3: Best Fit Model Parameters and Statistics, CPV

| $\Delta m^2_{41}$ (eV <sup>2</sup> ) | $\Delta m^2_{51}$ (eV <sup>2</sup> ) | $ U_{e4} $ | $ U_{\mu 4} $ | $ U_{e5} $ | $ U_{\mu 5} $ | p<br>(%) | _p<br>(%) | φ <sub>54</sub><br>(rad) | $\chi^2$ | d.o.f. | Signal input after cuts (10 <sup>21</sup> p.o.t.) | Background  | p/δp<br>(σ) | $p/\delta \overline{p}$ $(\sigma)$   |      |      |
|--------------------------------------|--------------------------------------|------------|---------------|------------|---------------|----------|-----------|--------------------------|----------|--------|---|---|-------------|--|------|------|
| 0.91                                 | 21                                   | 0.123      | 0.185         | 0.044      | 0.211         | 0.127    | 0.139     | 1.91π                    | 135.14   | 145    | ~300  | ~300  | ~300        | $v_{\mu}$ Mis-ID 353<br>$\Delta \Rightarrow N\gamma$ 1077<br>$v_{\varepsilon}$ (K <sup>+</sup> ) 116 | 4.52 | 3.57 |
| 0.92                                 | 24                                   | 0.129      | 0.149         | 0.063      | 0.164         | 0.105    | 0.121     | 1.82π                    | 140.8    | 146    |   | $\begin{vmatrix} v_{\varepsilon}(K) & 110 \\ v_{\varepsilon}(K^{0}) & 38 \\ v_{\varepsilon}(K^{0}) & 192 \end{vmatrix}$ | 3.60        | 3.07   |      |      |

with atmospheric constraint

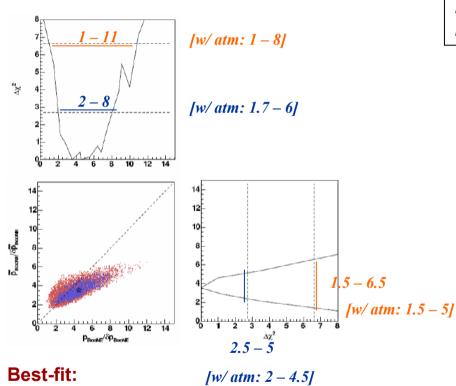
### CP-conserving (3+2) models



without atm constraint

with atm constraint

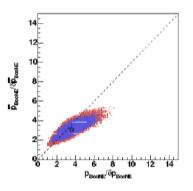
#### CP-violating (3+2) models



higher significance in v mode due to higher event statistics

#### **Best-fit (atm):**

$$\overline{p}_{BooNE} / \delta \overline{p}_{BooNE} \approx 3.1$$
 $p_{BooNE} / \delta p_{BooNE} \approx 3.6$ 



$$\overline{p}_{BooNE} / \delta \overline{p}_{BooNE} \approx 3.5$$
 $p_{BooNE} / \delta p_{BooNE} \approx 4.5$ 

without atm constraint

with atm constraint

# Results: CPV phase space and CP asymmetry

allowed ( $p_{BooNE}$ ,  $\bar{p}_{BooNE}$ ) space for varying CPV phases is generated with neutrino masses and mixings fixed to their best fit values

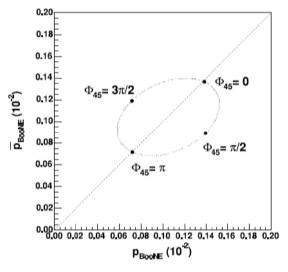
only CPV phase  $\varphi_{54}$  is allowed to vary over  $[0, 2\pi]$ 

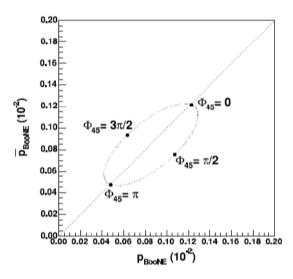
CP asymmetry significance  $A_{CP}/\delta A_{CP}$  is plotted as a function of CPV phase

CP asymmetry  $A_{CP} = (p_{BooNE} - \overline{p}_{BooNE}) / (p_{BopNE} + \overline{p}_{BooNE})$ 

 $\delta A_{CP}$  calculated assuming  $\delta p_{BooNE}$  and  $\delta \overline{p}_{BooNE}$  are uncorrelated

## Results: CPV phase space





$$\varphi_{54} = arg(U^*_{\mu 5} U_{e5} U_{\mu 4} U^*_{e4})$$

Fixed parameters (CPV best-fit model):

$$\Delta m^2_{41} = 0.91 eV^2$$
,  $\Delta m^2_{51} = 21 eV^2$ ,  $|U_{e4}| = 0.123$ ,  $|U_{\mu 4}| = 0.185$ ,  $|U_{e5}| = 0.044$ ,  $|U_{\mu 5}| = 0.211$ 

Fixed parameters (CPV+atm best-fit model):

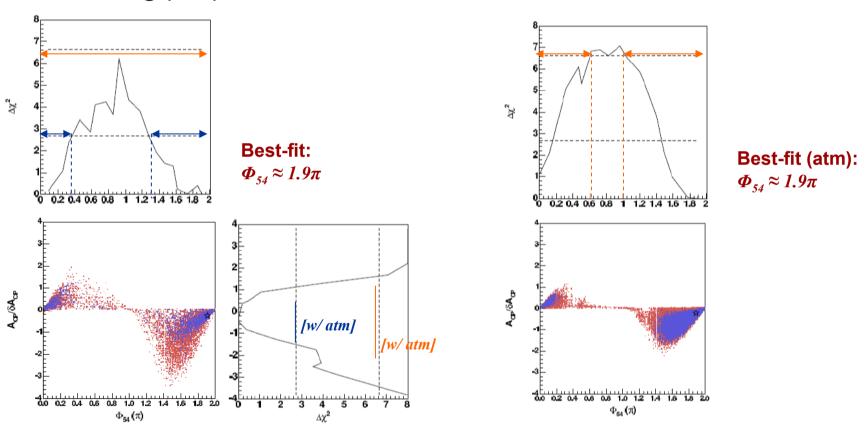
$$\Delta m^2_{41} = 0.92 eV^2, \quad \Delta m^2_{51} = 24 eV^2,$$
 $|U_{e4}| = 0.129, \quad |U_{\mu 4}| = 0.149,$ 
 $|U_{e5}| = 0.063, \quad |U_{\mu 5}| = 0.164$ 

without atm constraint

with atm constraint

# Results: CP asymmetry

## CP-violating (3+2) models



without atm constraint

with atm constraint

## Conclusion

Combined analysis of all SBL oscillation results allow for all possible CPV phase values

CP violation could significantly affect MiniBooNE oscillation expectations, depending on running mode (neutrino vs. antineutrino)

Atmospheric constraints support the above results, with no significant differences

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# Part III: Owl Shifts at the MiniBooNE Control Room